

Experimental investigation of a thermoacoustic-Stirling refrigerator driven by a thermoacoustic-Stirling heat engine

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Abstract

In this paper, a thermally-driven thermoacoustic refrigerator system without any moving part is reported. This refrigeration system consists of a thermoacoustic-Stirling heat engine and a thermoacoustic-Stirling refrigerator; that is, the former is the driving source for the latter. Both the subsystems are designed to operate on traveling-wave mode. In the experiment, it was found that the DC-flows had significant negative effect on the heat engine and the refrigerator. To suppress these DC-flows, two flexible membranes were inserted into the two subsystems and worked very well. Then extensive experiments were made to test the influence of different parameters on refrigeration performance of the whole system. The system has so far achieved a no-load temperature of -65°C , a cooling capacity of about 270 W at -20°C and 405 W at 0°C ; in fact, the result showed a good prospect of the refrigeration system in room-temperature cooling such as food refrigeration and air-conditioning.

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1. Introduction

Energy-saving and environment-protection are the two main issues of future sustainable development of the world. Currently, there is an urgent task to replace chlorofluorocarbon (known as CFC) refrigeration that has produced serious ODP (ozone depletion potential) and GWP (global warming potential) problems. Thermoacoustic refrigeration uses inert gas as working substance; as a result, it is expected to be a good solution to the problems. In addition, thermoacoustic refrigeration can be powered by thermal energy like solar energy and other waste heat; thus, it is also considered as an energy-saving refrigeration method.

A thermoacoustic refrigerator may be driven electrically or thermally. The former uses a mechanical compressor, while the latter simply uses heat energy as driving source. Regarding thermally driven thermoacoustic refrigeration, nowadays, there are two interesting directions:

one aiming at cryogenic cooling and the other aiming at room temperature cooling. The current focus of cryogenic thermoacoustic refrigeration is to achieve lower temperature while the focus of room-temperature cooling is to improve efficiency. In particular, the room-temperature thermoacoustic refrigeration has obtained more attention worldwide due to its huge commercial prospect if it can replace the CFC refrigeration. In fact, many previous thermoacoustic refrigerators on room-temperature cooling have been tested in the past decades. Some of them were driven electrically [1–3], while others were driven thermoacoustically [4]. However, these thermoacoustic refrigerators nearly operate on standing-wave mode in which they have to experience irreversible heat transfer and thermodynamic processes; consequently, their efficiencies are much lower than that of the CFC refrigeration. Recently, there are some researches on searching for efficient operation of thermoacoustic refrigerators [5–8].

In this paper, a thermoacoustically driven thermoacoustic refrigerator with double thermoacoustic-Stirling cycles is reported. In the system, the energy-focused thermoacou-

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stic-Stirling heat engine replaces those commonly-used, standing-wave thermoacoustic heat engines; as a result, the overall performance of the thermoacoustic-Stirling refrigerator is greatly improved. So far, the refrigerator has achieved a no-load temperature of -65°C , a cooling capacity of about 270 W at -20°C and a cooling capacity of 405 W at 0°C . Detailed results will be described in the following sections.

2. Experimental system

As mentioned above, the experimental system studied here is a thermoacoustically driven, thermoacoustic refrigerator. It includes two main subsystems, a thermoacoustic-Stirling heat engine and a thermoacoustic-Stirling refrigerator, shown in Fig. 1. The thermoacoustic-Stirling heat engine mainly consists of a traveling-wave loop and an energy-focused resonator. The traveling-wave loop is composed of an inertance tube (also called feedback tube), a compliance bulb, a main after-cooler, a regenerator, a heater exchanger, a thermal buffer tube and a secondary after-cooler in counterclockwise direction. By carefully designing these thermodynamic components, it is possible to make the regenerator operating on efficient thermoacoustic-Stirling cycle. In addition, the resonator is also critical to efficient operation of the thermoacoustic heat engine. In the energy-focused thermoacoustic-Stirling heat engine, a specially designed, tapered resonator is used to avoid nonlinear losses resulting from excitation of harmonic wave or even shock wave in an iso-diameter resonator. The structure parameters of the thermoacoustic heat engine can be found elsewhere [8]. Before coupling with the thermoacoustic-Stirling refrigerator, extensive tests on the performance of the thermoacoustic heat engine have been tested.

On the other hand, the thermoacoustic-Stirling refrigerator was designed more early. The initial objective of designing the thermoacoustic-Stirling refrigerator was to demonstrate if it could work better than those standing-wave thermoacoustic refrigerators. Interestingly, the thermoacoustic-Stirling refrigerator has a very similar traveling-wave loop as the thermoacoustic-Stirling heat engine. It also includes a feedback tube, a compliance bulb, a main after-cooler, a regenerator, a cold heat exchanger, a ther-

mal buffer (like pulse tube) and a secondary after-cooler. The structure parameters of the refrigerator were described in Ref. [9]. Basically, its structure parameters are optimized for 2.0 MPa helium gas operating at 50 Hz. In 2003, the thermoacoustic-Stirling refrigerator was first time tested by coupling with our standing-wave thermoacoustic heat engine. At a resonant frequency of about 85 Hz, the refrigerator achieved a cooling capacity of about 30 W at -20°C and about 100 W at 0°C . This was the first time that the refrigerator made frost! By simply changing the resonator length to achieve a resonant frequency of about 57 Hz, the thermoacoustic refrigerator eventually achieved a cooling power of about 80 W at -20°C .

Encouraged by the above-mentioned results, we determined to integrate the thermoacoustic-Stirling heat engine and the thermoacoustic-Stirling refrigerator together though they may not match each other. It is still expected that the integrated system with double thermoacoustic-Stirling cycles may achieve a better performance. And this is the objective of the work.

3. Experimental results and discussion

In the experiment, it was found that the DC-flow [10] exists in the two traveling-wave systems and has a significant negative impact on the performance of the two subsystems. Therefore, two elastic membranes capable of suppressing the DC-flow were used in the thermoacoustic-Stirling heat engine and the thermoacoustic-Stirling refrigerator. Fig. 2a shows the influence of the DC-flow on pressure ratio of the thermoacoustic-Stirling heat engine. Indeed, the DC-flow has serious negative effect to the thermoacoustic-Stirling heat engine. Fig. 2b shows the DC-flow on the cooling capacity of the thermoacoustic-Stirling refrigerator. It can be seen that the refrigerator without the membrane achieved a lowest temperature of about 280 K, whereas the refrigerator with the membrane achieved a lowest temperature of about 256 K and a cooling capacity of 50 W.

Extensive experiments were done after using the elastic membranes. Fig. 3 shows the cooling performance of the refrigerator with 3.0 MPa pressure under different input heats. It shows that the refrigerator can achieve lower temperature and larger cooling capacity with higher input heat. For 3.0 MPa averaged pressure, the refrigerator achieved a lowest temperature of about -65°C and a cooling capacity of 270 W at -20°C under an input heat of about 2.2 kW; in addition, even with 500 W heating power, the refrigerator still achieved a lowest temperature of about -30°C .

Both the thermoacoustic-Stirling heat engine and the thermoacoustic-Stirling refrigerator were designed based on helium gas, so the above-mentioned experiments were tested with helium gas. However, the following experiments were performed for comparison between helium gas and nitrogen gas. Fig. 4 gives a comparison result between with helium gas and with nitrogen gas. This figure shows that the refrigerator with helium gas works better than with nitrogen gas. Nevertheless, the nitrogen-based refrigerator

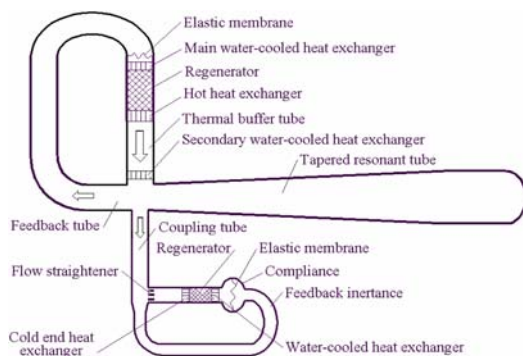


Fig. 1. The non-moving-part refrigerator system based on double thermoacoustic-Stirling cycles.

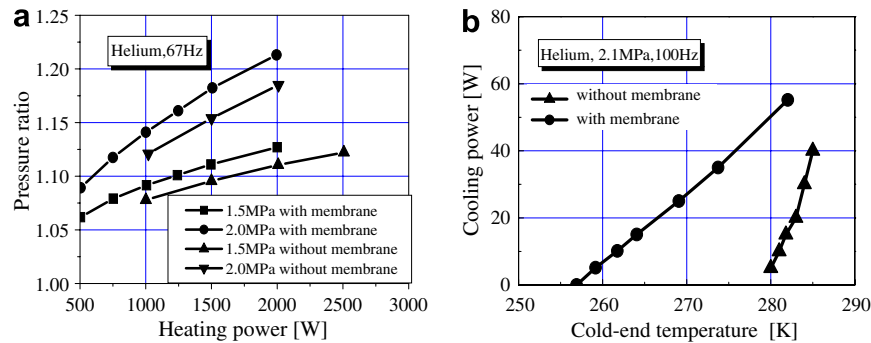


Fig. 2. The influence of DC-flow on the thermoacoustic-Stirling heat engine and refrigerator (a) heat engine and (b) refrigerator.

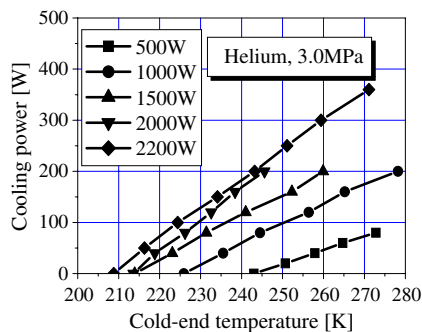


Fig. 3. Cooling performance under different heating powers (helium gas).

still achieved a lowest temperature of about -45°C and a cooling capacity of about 45 W at -20°C under 1.5 MPa averaged pressure. This is not surprising because the refrigerator is basically designed based on helium gas. However, the authors believe that nitrogen gas can work well as helium gas if the refrigerator parameters are optimized for nitrogen gas.

4. Summary

In this work, a thermoacoustically driven refrigerator based on double thermoacoustic-Stirling cycles is developed and tested. The experiment shows that the DC-flow indeed has significant negative impact on the performance of both the thermoacoustic-Stirling heat engine and refrigerator. Suppression of the DC-flow is critical to efficient operation of the thermoacoustic systems. Two elastic mem-

branes are used to suppress the DC-flow in our system successfully. The whole system is tested under different operating conditions including averaged pressure, input heat and working gas. With 3.0 MPa helium gas, the refrigerator achieved a lowest temperature of about -65°C and a cooling capacity of about 270 W at -20°C and 405 W at 0°C . Moreover, nitrogen gas was also tested to make a comparison with helium gas. With 1.5 MPa nitrogen gas, the refrigerator achieved a lowest temperature of about -45°C . These preliminary results showed a good prospect of application of the thermoacoustic refrigeration in room-temperature cooling in near future.

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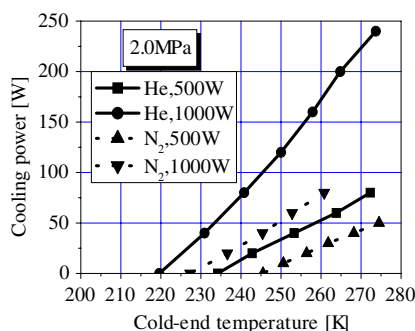


Fig. 4. Comparison between helium and nitrogen.